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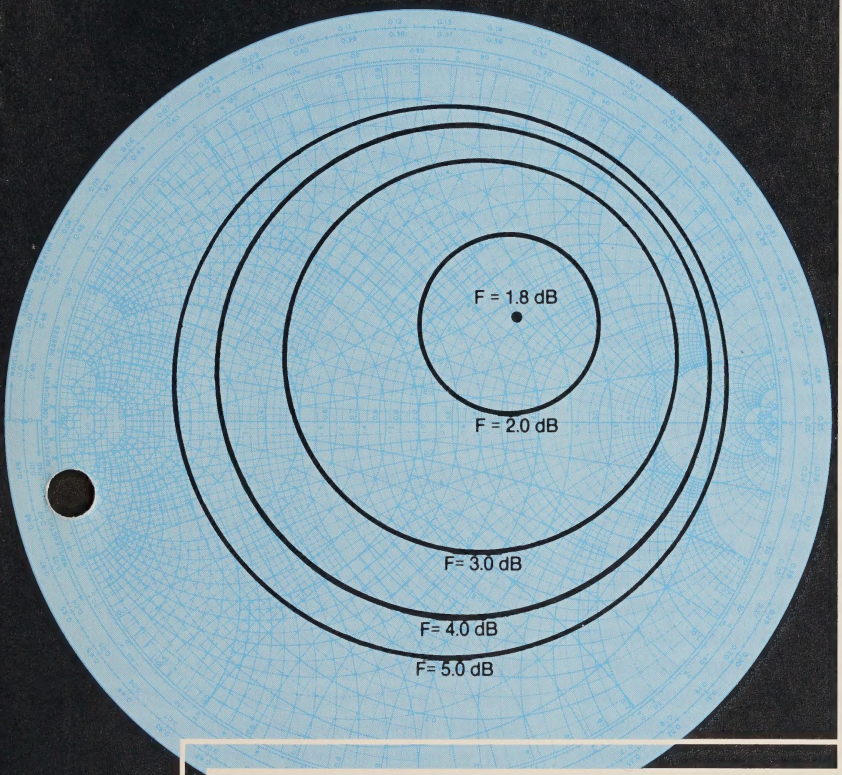
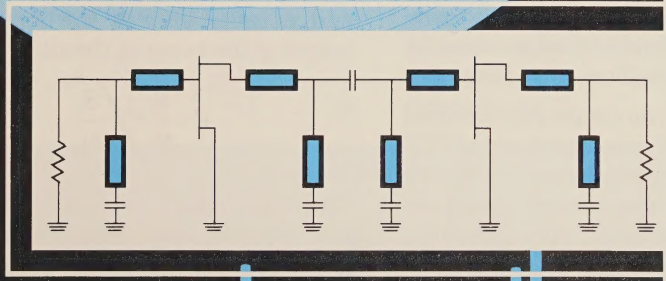
Measurement of GaAs FET Noise Parameters





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Tech-notes

In many microwave receiving systems the level of the noise floor, hence, also the system sensitivity, is largely determined by the performance of the first rf amplifier. This fact has spurred the last two decades' development of low-noise Gallium Arsenide Field Effect Transistors (GaAs FETs) for use as amplifying devices at microwave frequencies. Designers of low-noise amplifiers have an ever-increasing variety of high-performance transistors at their disposal, but to choose the best device out of those available, and to design a circuit which takes full advantage of its capabilities, requires that transistor noise properties be characterized in some way.

Noise properties can be quantified through the concepts of minimum noise figure and noise match. The minimum noise figure of a device describes the best performance (in terms of lowest noise) of which it is capable, and the noise match describes the circuit conditions under which the minimum noise figure will be obtained. For designers, these quantities can be just as important as S-parameters for comparing devices from different manufacturers and for circuit design. Standard definitions of minimum noise figure and noise match exist, so all the groundwork is in place for making valid comparisons of different transistors and for executing optimal low-noise designs.

Unfortunately, no simple standardized method exists for measurement of FET noise parameters at microwave frequencies. The measurements made are usually sophisticated, labor-intensive, and not always well understood by those making them. Thus, there is a need for a way of making fast, reliable measurement of noise parameters. Such a method, if standardized, would simplify the problem of comparing the noise specifications given by device manufacturers, because all their measurements could be made in the same way and to similar accuracy. With the recent advent of techniques for rf probing of FET chips at microwave frequencies, it is also possible that FETs could be individually qualified for use in production of a particular amplifier design.

This article explains the problems involved in noise-parameter measurements and describes some recent work at Watkins-Johnson Company toward the goal of rapid, automated measurement of noise parameters. It is hoped that the article will increase the reader's understanding of noise parameters and low-noise design, whether he or she is involved in the use of low-noise transistors directly, or in the use or specification of low-noise amplifiers and receiving systems.

Noise Figure

Before discussing the nature and measurement of FET noise parameters, it is useful to summarize the definition and properties of the quantity known as *noise figure*. The noise figure, F, of a microwave two-port circuit is defined as the ratio of two signal-to-noise ratios; namely, the ratios of available signal and noise powers at the input and output of the two-port circuit:[1]

$$F = \frac{S_i}{N_i} \Big/ \frac{S_o}{N_o} \qquad (1)$$

The input noise is assumed to be thermal noise at some reference temperature, T, usually chosen to be 290° Kelvin. The noise figure is a measure of the amount by which the two-port circuit causes the signal-to-noise ratio to degrade between input and output. In terms of the reference temperature, the available gain, Ga, of the two-port circuit, and the available noise,

N_a, added by the two-port circuit to its output signal, the noise figure becomes,

$$F = \frac{G_a KT + N_a}{G_a KT}, \quad (2)$$

where, K is Boltzmann's constant and all powers are referenced to a bandwidth of one Hertz.

When several individual two-port circuits are combined in a cascade, the input noise floor at any given stage will differ from the thermal level due to the action of stages preceding it. The individual noise figures combine to give an overall noise figure as,

$$F_{tot} = F_1 + \frac{F_2 - 1}{G_{a1}} + \frac{F_3 - 1}{G_{a1}\, G_{a2}} + \ldots \quad (3)$$

Noise Parameters

In 1956, Rothe and Dahlke[2] showed that the noise figure of an active device such as a FET varies with circuit tuning. Having some description of the tuning dependence of F is clearly very important to low-noise design. This dependence is commonly expressed in terms of quantities called the noise parameters.

Rothe and Dahlke showed that the noise figure of a given device is independent of its load, but *does* depend on the source admittance as,

$$F = F_o + \frac{R_n}{G_s} \left| Y_s - Y_o \right|^2 \quad (4)$$

where, Y_s is the source admittance, G_s is the source conductance, F_o is the lowest noise figure attainable by the device, Y_o is the source admittance for which F_o is obtained, and R_n is a parameter showing how fast F increases as Y_s departs from Y_o. F_o, R_n and Y_o are the noise parameters of the device in question. In general, the noise parameters of a given FET are functions of frequency, temperature, and dc bias. Once known, the noise parameters can be used to predict the noise figure of the FET under any circuit conditions.

Measuring Noise Figure

Measurement of noise figure is basic to measurement of the noise parameters. Most noise-figure measurement schemes are based on measuring output noise from the FET using a power detector of known bandwidth and a source whose noise output power is also known. Two measurements at different input levels are required to distinguish added noise from gain. Therefore, modern noise-figure meters are made to work in conjunction with a noise source whose output can be switched between two known levels. Figure 1 shows schematically a noise-figure measurement using a source which switches between output levels corresponding to room temperature, T_1, and an elevated temperature, T_2.

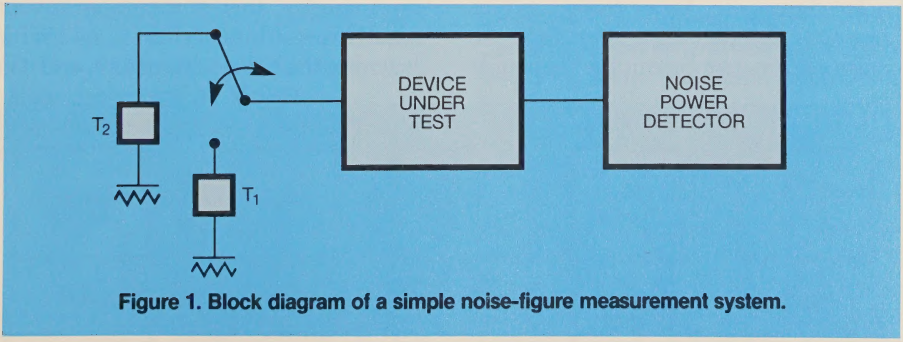

Figure 1. Block diagram of a simple noise-figure measurement system.

Assuming the detector in the figure has a bandwidth of one Hertz and the FET has gain and added noise power, G_a and N_a, the two output power levels which will be measured by the detector are,

$$N_1 = kT_1G_a + N_a$$
$$N_2 = kT_2G_a + N_a \quad (5)$$

Using equation 2 for N_a in terms of the noise figure gives,

$$F = (T_2-T_1)N_1 \Big/ [T_1(N_2-N_1)] \quad (6)$$

after eliminating G_a. Within the limits imposed by the sensitivity of the detector, equation 6 is true regardless of whether the detector is matched to the output of the FET, even though N_1 and N_2 can vary with the output match.

Measuring Noise Parameters: Direct Methods

Perhaps the simplest way of measuring FET noise parameters that one might envision would be to tune on the source admittance presented to the FET until the noise figure is seen to reach a minimum. At this point, F_o is the observed minimum noise figure, and a vector measurement of the source admittance gives, Y_o. Connecting the FET to a 50-ohm source and measuring its noise figure then allows calculation of R_n. There are any number of ways this basic method can be implemented, based on use of different ways of tuning the source, different ways of measuring noise figure, etc. All of these have in common the fact that they find the noise parameters by tuning the source admittance directly onto Y_o, so they will be referred to as direct methods.

A simple setup for direct manual measurement of noise parameters is shown in Figure 2. Here, the noise-figure meter is assumed to be one which gives continuous readout of noise figure and insertion gain. The figure shows manual tuners in series with the input and output of the FET. It is assumed that the S-parameters of the FET chip and its mounting structure are already known.

To make a measurement, the input tuner is adjusted for minimum noise figure and the output tuner for maximum gain. The S-parameters of the tuners are then measured at their optimum settings, available gains calculated, and equation 3 used to extract the minimum noise figure of the FET from the cascade of tuners, FET, and mounting structure. Knowledge of the input tuner S-parameters allow calculation of the optimum source admittance. Removing the input tuner and repeating the noise-figure measurement would then determine R_n.

The "cost" of this measurement is careful tuner manipulation, two measurements of tuner S-parameters, and some calculations. Measurement of FET S-parameters is not considered part of the cost of the noise parameters, since S-parameters are needed for amplifier design anyway. As will be seen shortly, this is a comparatively small expenditure of effort in return for learning the noise parameters, and it is

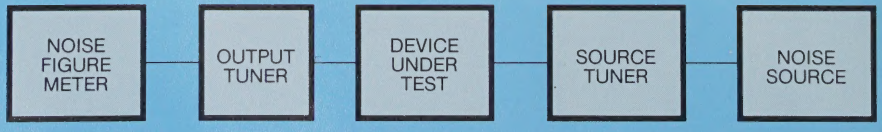

Figure 2. Block diagram of a system for manual measurement of noise parameters.

characteristic of direct methods that a comparatively small number of actual measurements are necessary to get the desired results.

However, direct methods *do* have inherent drawbacks in terms of accuracy and suitability for automation. The accuracy problems have to do with the fact that the measurement minimizes the noise figure of the tuner/FET/tuner cascade. First, it is possible that variations in tuner available gain can hide the true minimum in the FET noise figure. If so, the measurement will be made at something other than the lowest noise operating point of the FET. Second, searching for minimum noise figure is inherently difficult, since the noise figure changes very slowly with source admittance in the neighborhood of its minimum.

Problems with automation stem from the fact that direct methods must depend on tuning the source onto Y_0, exactly. This implies that some tuning structure must be used which is continuously variable and which can reach all the admittances on the Smith chart. In an automated system, continuous variations might be accomplished electronically using varactor diodes, but limitations on varactor Q would prevent reaching all parts of the Smith chart. Mechanical tuning using stepping motors is an alternative, but it is bulky and not simple to interface to a measurement system of modest size.

Measurement of Noise Parameters: Indirect Methods

There is a second category of noise-parameter measurement methods which do not suffer from the drawbacks just described. These will be referred to as *indirect methods.* Indirect methods of measurement are more complicated in concept than direct methods, but they are better suited for automation. Indirect methods are based on measuring the noise figure of the FET in question at four or more distinct values of source admittance, none of which need to be equal to Y_0. Plugging the set of source admittances and their corresponding noise figures into equation 4 gives a set of conditions which determines the noise parameters. A total of four source admittances is enough to determine the noise parameters, but it is customary to use more than four admittances and some kind of averaging on the results to lessen the effects of experimental errors.

It is instructive to compare an indirect manual measurement to the direct one already described. The indirect measurement uses the same setup shown in Figure 2. Four or more input tuner settings are chosen and the corresponding noise figures recorded. The tuner S-parameters are then measured at every setting used and the FET noise figure and source admittance for each setting are calculated. Finally, these results would be used with equation 4 to find the noise parameters.

The "cost" of the indirect method is careful tuner manipulation (though less demanding than for the direct method), at least four measurements of noise figure and tuner S-parameters, and more calculation than for the direct method. Thus, indirect measurement involves more effort than does direct measurement. The benefit derived from the extra effort is that the inaccuracy resulting from the direct search for minimum noise figure is greatly reduced. Indirect measurement also places fewer demands on the source tuner. Since Y_0 need not be reached exactly, a tuner which only reaches a set of distinct points on the Smith chart can be used. Therefore, the tuner can take the form of a simple switched filter, and it can be easily

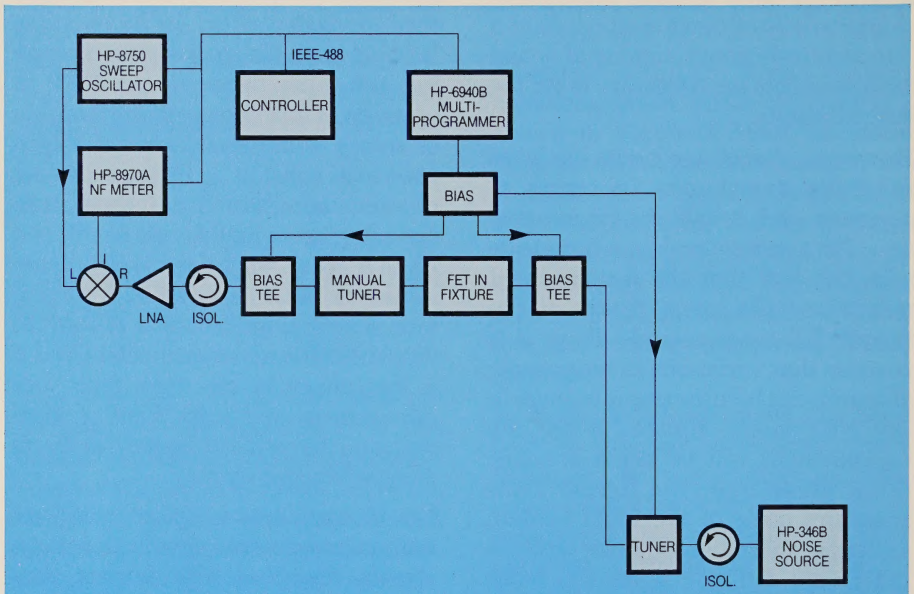

Figure 3. Block diagram of noise-figure measurement system incorporating a switched tuner.

realized and electronically controlled using switching diodes.

A System For Automated Measurements: Some Practical Considerations

Automated noise-parameter measurement experiments have been performed at Watkins-Johnson Company using an indirect approach with a switched tuner. The system used is shown in simplified block form in Figure 3. To make a measurement, the system controller issues commands to switch tuner settings and cue the noise-figure meter, as well as to control dc bias to the FET and to set the measurement frequency. Each of the elements in the measurement cascade shown in the figure is defined by APC-7 input and output connectors, so that reference planes for all requisite S-parameters are well defined. After a series of noise-figure measurements is complete, the same controller drives the tuner through its settings for S-parameter measurements on an automatic network analyzer.

Figure 4 is a photograph of the switched input tuner. The tuner consists of a 50-ohm microstrip throughline, along which are distributed PIN switching diodes in shunt. Each diode is connected to rf ground through a small inductance. Each inductance serves as a path to bring in a dc control signal and as an rf discontinuity which changes the output admittance of the tuner when the corresponding diode is turned on.

The measurement system in Figure 3 includes several elements not shown in Figure 2: bias tees, isolators, a low-noise amplifier, and a mixer. In theory, these elements are not essential to the measurement, but in practice they are needed to make accurate results possible. The need for dc bias networks is obvious, though it is possible to build these into the FET text fixture rather than to use separate bias tees. The function of the mixer is to convert the microwave noise produced by the FET to the input frequency range accepted by the noise-figure meter. The low-noise

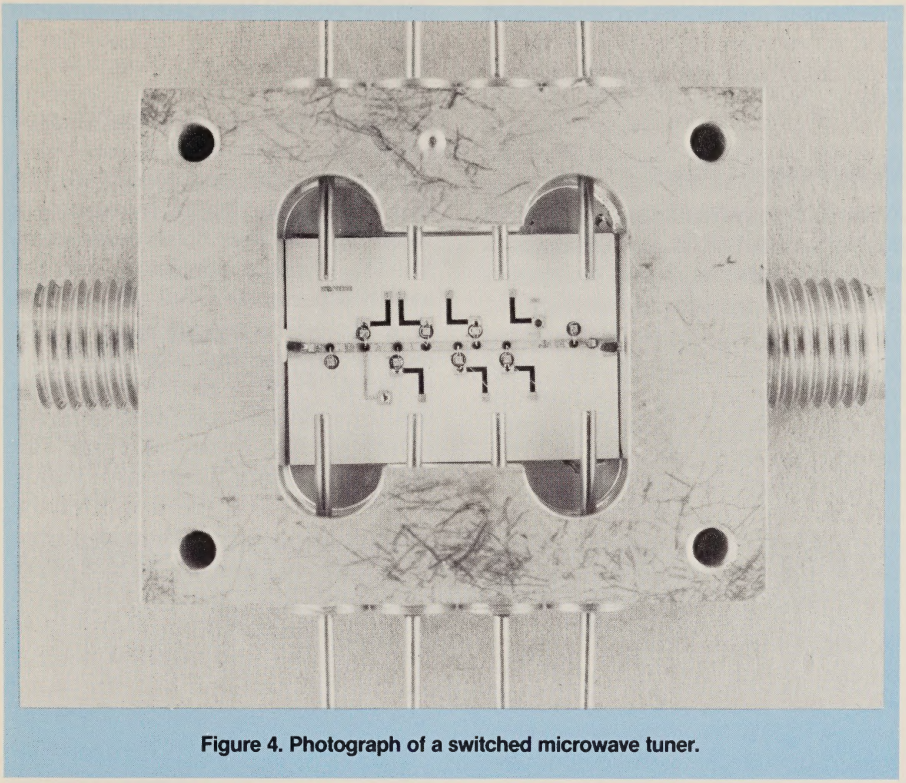

Figure 4. Photograph of a switched microwave tuner.

amplifier (LNA) helps negate the effects of noise added by the mixer and within the meter. The isolator preceding the LNA presents the LNA with a constant source admittance during calibration and measurement. Thus, it protects the validity of the calibration, since the noise figure of the LNA can itself change according to equation 4.

The meter, mixer, LNA and isolator can be considered to form a composite noise-figure "meter." Calibration of the composite meter is the same as for a single noise-figure meter. The source of two known noise temperatures are connected to the input of the meter (in this case, Port 1 of the isolator) and the gain and added noise of the meter are measured.

Figure 3 shows a second isolator between the noise source and the input tuner. Its role is to minimize effects due to noise-source mismatch. Most real noise sources are not perfectly matched to 50 ohms. Instead, a typical source has a small but finite mismatch to 50 ohms and, more importantly, its output admittance changes when the source switches from one noise temperature to another. Without the isolator, this change would give rise to a change in the source admittance seen by the FET, and could render the measurement inaccurate. The presence of the isolator assures that the source admittance seen by the FET will be the same at both source temperatures.

Care must be taken in how isolators are treated in network calculations. Their available gain is a function of the match at their input port, so mismatches which occur during measurement must be accounted for in order to obtain accurate results. Fortunately,

the effects of mismatch can be predicted from measurements of S-parameters, so making the proper corrections is not difficult.

Measurement Results

From the measurements and calculations described earlier, one obtains a set of source admittances and their corresponding transistor noise figures. According to theory, the relationships between the admittances and noise figures must obey equation 4, provided the correct values of the noise parameters are used in the equation. This suggests that the noise parameters could be found by substituting any four (Y_S, F) points into the equation to produce four conditions on the noise parameters.

Because of experimental error, however, few or none of the measured (Y_S, F) points will obey equation 4, exactly. Because of this, the usual way of calculating the noise parameters is to perform some type of fitting to more than four measured points. There are a number of ways in which this can be done, depending on whether the experimental error is expected primarily to have affected the Y_S values, the F values, or both.

A scheme which assumes roughly equal effects from error in both Y_S and F was developed by Mitama and Katoh.[3] In this scheme, one begins by assuming values for the four noise parameters. The (Y_S, F) points consistent with the assumed parameters fall on a surface in a three-dimensional space whose rectangular coordinates are (G_S, B_S, F). Each (Y_S, F) point resulting from the measurements is assigned an error equal to its distance from the theoretical surface, as shown in Figure 5. The distance is the length of the shortest line segment connecting the measured point to the surface. Adding up all the errors from the individual points yields an error sum. An iterative process is used to adjust the values of the noise parameters until the error sum reaches its minimum value, at which point the best fit to the measured data is assumed to have been obtained.

Figures 6 and 7 show final results from automated noise parameter measurements performed on a Watkins-Johnson

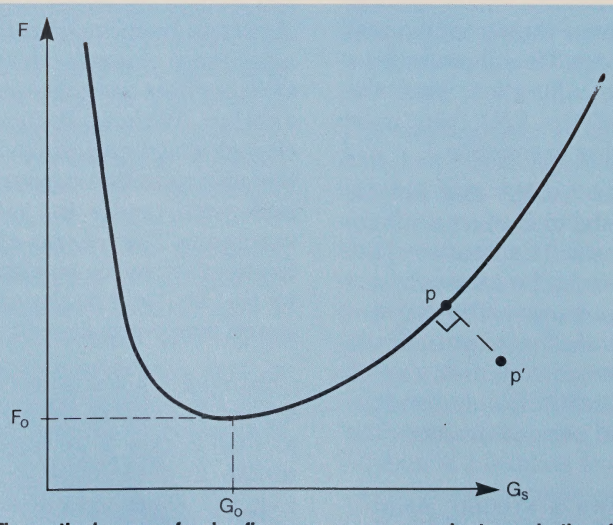

Figure 5. Theoretical curve of noise figure vs. source conductance in the plane, B_S=B_o.

Company F105R GaAs FET in X-Band. Figure 6 shows the calculated optimum source impedances for minimum noise figure over 8 to 10 GHz. Figure 7 shows contours of constant noise figure in the source impedance plane for the same transistor at 10 GHz. The contours are circles as a result of the form of equation 4.[4]

The Future Outlook

At present, accurate determination of GaAs FET noise parameters remains as one of the frontiers of microwave measurement. It is inherently one of the most complex aspects of FET characterization, requiring S-parameter measurements, noise figure measurements, and much data reduction in order to produce good results. Fortunately, the sheer volume of effort involved in noise-parameter measurement has been substantially reduced by the advent of automated network analyzers and noise-figure meters, together with programmable controllers.

As for standardization of noise-parameter measurement, nearly all of the requisite hardware is already commercially available. All of the equipment used in the measurements described are standard instruments

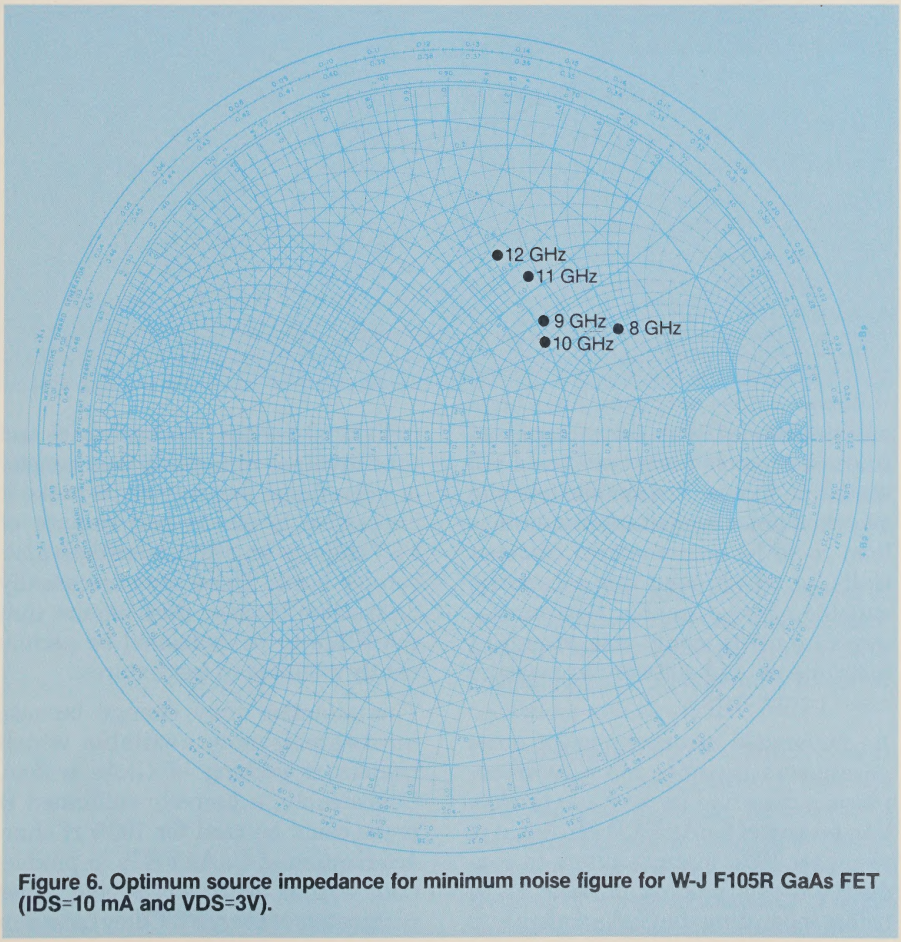

Figure 6. Optimum source impedance for minimum noise figure for W-J F105R GaAs FET (IDS=10 mA and VDS=3V).

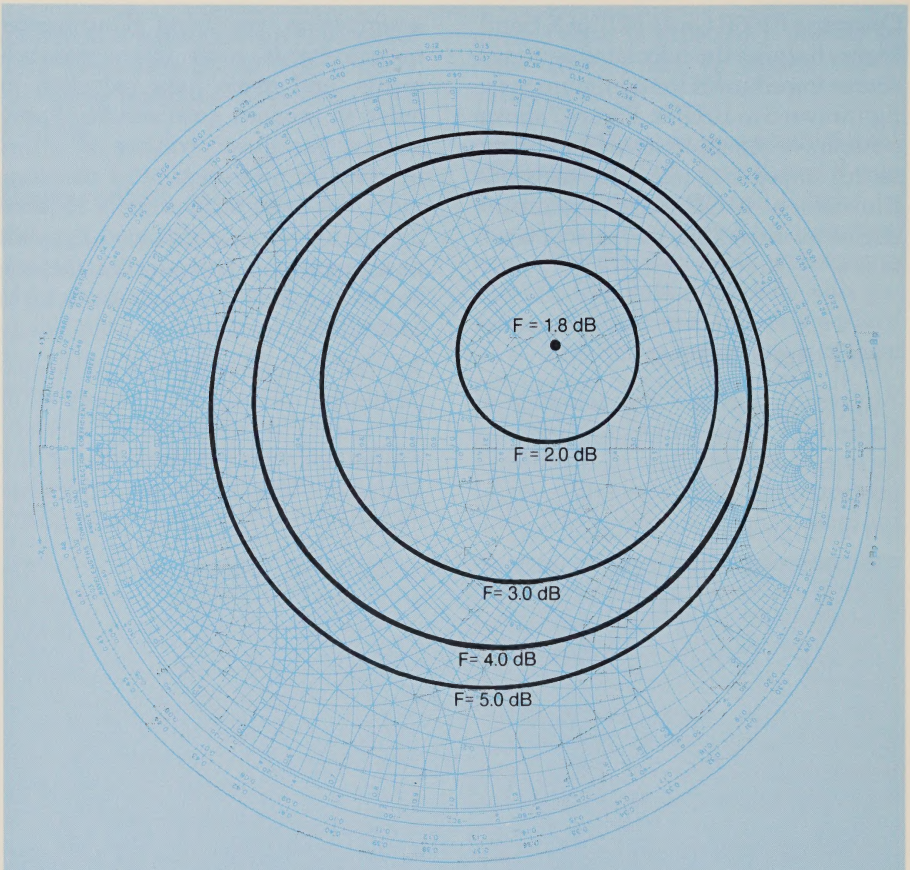

Figure 7. Source-impedance contours for constant noise figure for W-J F105R GaAs FET (IDS=10 mA and VDS=3V).

and accessories, with the exception of the noise-match tuner and the FET mounting fixture. The simplicity of the switched tuner suggests that a similar item could be manufactured commercially, at which point any laboratory capable of good quality S-parameter measurements could use standard instruments and software to measure noise parameters.

As automated measurement of noise parameters becomes more commonplace, it may find its way into production testing of GaAs FETs. Today, it is usual for FET manufacturers to conduct 100% dc probing of their FETs before separating the GaAs wafers into individual devices. The intricacies and time involved in making S-parameter or noise-figure measurements make it impossible to test rf performance of FET chips on anything more than a lot-sample basis. These tests are usually destructive because they require that the FETs to be evaluated be permanently mounted in test fixtures.

This situation may change because hardware is now available which enables rf probing of GaAs wafers. Conceivably, a properly calibrated rf probe could be used for 100% rf characterization of GaAs FETs in production. Armed with the S- and noise parameters of every FET they have pur-

chased, circuit manufacturers could increase their yields by predicting whether an individual FET is suitable for any particular application. The cost of performing such a tremendous volume of accurate rf measurements might be prohibitive today, but it will undoubtedly become more and more affordable as time goes on.

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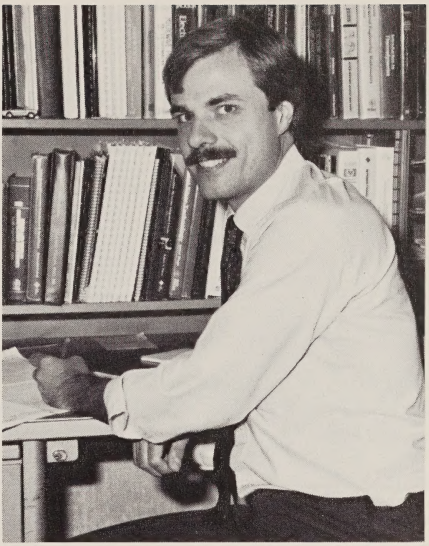

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